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Colorado Ultraviolet Transit Experiment: a dedicated CubeSat mission to study exoplanetary mass loss and magnetic fields

Brian T. Fleming,^{a,*} Kevin France,^a Nicholas Nell,^a Richard Kohnert,^a Kelsey Pool,^a Arika Egan,^a Luca Fossati,^b Tommi Koskinen,^c Aline A. Vidotto,^d Keri Hoadley,^e Jean-Michel Desert,^a Matthew Beasley,^f and Pascal M. Petit^g

^aUniversity of Colorado, Laboratory for Atmospheric and Space Physics, Boulder, Colorado, United States

^bAustrian Academy of Sciences, Space Research Institute, Graz, Austria

^cUniversity of Arizona, Lunar and Planetary Laboratory, Tucson, Arizona, United States

^dUniversity of Dublin, Trinity College Dublin, School of Physics, Dublin, Ireland

^eCalifornia Institute of Technology, Pasadena, California, United States

^fPlanetary Resources LLC, Redmond, Washington, United States

^gUniversité de Toulouse, IRAP, CNRS, CNES, UPS, Toulouse, France

Abstract. The Colorado Ultraviolet Transit Experiment (CUTE) is a near-UV (2550 to 3300 Å) 6U CubeSat mission designed to monitor transiting hot Jupiters to quantify their atmospheric mass loss and magnetic fields. CUTE will probe both atomic (Mg and Fe) and molecular (OH) lines for evidence of enhanced transit absorption, and to search for evidence of early ingress due to bow shocks ahead of the planet's orbital motion. As a dedicated mission, CUTE will observe ≥ 100 spectroscopic transits of hot Jupiters over a nominal 7-month mission. This represents the equivalent of >700 orbits of the only other instrument capable of these measurements, the Hubble Space Telescope. CUTE efficiently utilizes the available CubeSat volume by means of an innovative optical design to achieve a projected effective area of $\sim 28 \text{ cm}^2$, low instrumental background, and a spectral resolving power of $R \sim 3000$ over the primary science bandpass. These performance characteristics enable CUTE to discern transit depths between 0.1% and 1% in individual spectral absorption lines. We present the CUTE optical and mechanical design, a summary of the science motivation and expected results, and an overview of the projected fabrication, calibration, and launch timeline. © 2018 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.JATIS.4.1.014004](https://doi.org/10.1117/1.JATIS.4.1.014004)]

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1 Introduction

Small satellite missions enable the study of transient phenomena over extended time periods in a manner not feasible for large, multipurpose space observatories, such as HST. Long-term monitoring of exoplanets in short-period orbits (1 to 5 days) provides a unique opportunity to observe the interplay between planetary atmospheres and the host star. Repeatable, near-ultraviolet (NUV; 2550 to 3300 Å) transit spectroscopy enables quantification of the atmospheric mass loss and potentially planetary magnetic fields. The Colorado Ultraviolet Transit Experiment (CUTE) is the first NASA-funded UV/O/IR astrophysics CubeSat, and second overall (the first being the University of Iowa *x*-ray mission HaloSat). CUTE leverages a compact optical design in a 6U Cubesat form factor to provide a high-efficiency NUV spectrograph dedicated to monitoring the spectral properties of hot Jupiter atmospheres during transit.

The typical transit depth of hot Jupiters at visible wavelengths is $\sim 1\%$; however, the atmospheres of short-period planets may be inflated to several planetary radii, resulting in transit depths of 3% to 10% in specific spectral tracers.^{1,2} Some systems present late egresses indicative of the presence of

a cometary tail due to the planetary atmosphere being dragged by stellar wind and radiation as it extends beyond the Roche lobe. It is also possible that these planets will exhibit an early ingress indicative of atmospheric material preceding the planet in its orbit. NUV transit measurements of an early ingress in the close-orbiting WASP-12 system were interpreted due to an optically thick bow shock supported by either a planetary magnetic field^{3,4} or a high mass-loss rate.⁵

Observing time resources on orbiting observatories are insufficient to monitor enough transiting systems to statistically characterize the interplay between short period, massive planets, and their host stars. Broadband visible/NIR light curves, such as those generated by TESS or Kepler, are not sensitive to atmospheric tracers. The observation time necessary to establish a complete transit lightcurve for multiple systems, with multiple visits to each system to check for variability, is too costly for a shared flagship resource, such as HST. The time to completely map a transit for a single system is determined not by the sensitivity of the observatory, but rather by the length of time the planet is in-transit and the observational time available (set by the orbit of the spacecraft). As a dedicated satellite, CUTE will carry out the first survey of NUV spectral lightcurves of short-period exoplanets (Fig. 1).

*Address all correspondence to: Brian T. Fleming, E-mail: brian.fleming@lasp.colorado.edu

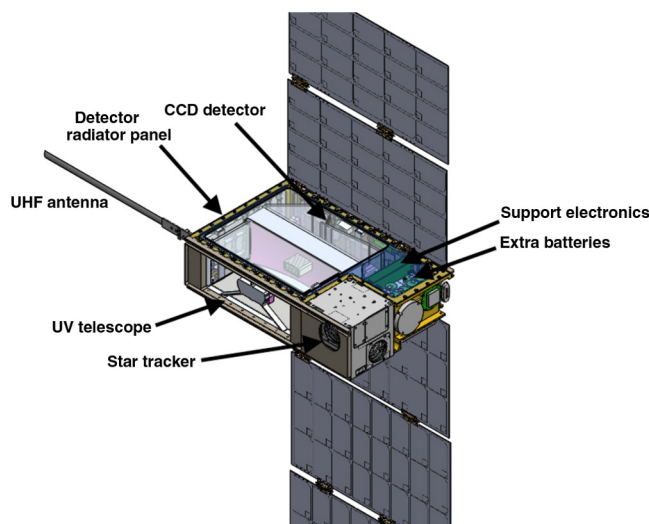


Fig. 1 Transparent rendering of the CUTE spacecraft.

The spectral resolving power of CUTE is comparable with the G230L mode of HST-COS ($R \approx 3000$) over a bandpass that covers critical atomic and molecular tracers, such as MgI, MgII, FeII, and OH, which are inaccessible from the ground. A compact design that maximizes throughput makes CUTE sensitive to transit depths of $>1.2\%$ in MgII to $>3\sigma$ confidence in a single transit for the median planet in the preliminary CUTE target list, and $>0.7\%$ in the continuum. Folded over multiple transits, the continuum sensitivity reaches down to $<1\%$ transit depths for all targets, and $<0.1\%$ for HD 209458b, respectively. In this paper, we will outline the motivation for CUTE (Sec. 2), provide an overview of the CUTE instrument design (Sec. 3), performance (Sec. 4), observation strategy (Sec. 5), and the integration and testing (I & T) timeline to launch (Sec. 6).

2 Scientific Background

Exoplanets in short-period orbits provide a laboratory to study extreme mass-loss from planetary systems with a small, dedicated satellite. To date, there are only a handful (<10) of published UV measurements of hot Jupiter atmospheres carried out with HST. The detection of hydrodynamic escape using UV measurements of Ly α , OI, CII, SiIII, and MgI^{6–8} led to

the development of multiple one- and three-dimensional models of the upper atmospheres of short-period planets (Fig. 2).^{9–12} The interpretation of many far-UV (FUV) transit measurements is controversial, however, due in part to the small-number statistics and uncertain spatial and temporal uniformity of the stellar FUV chromospheric emission.¹³

The NUV provides both higher stellar flux and a better understood spectral intensity distribution relative to the FUV,² as well as a diverse set of neutral, ionized, and molecular spectral lines that trace heavy elements.¹ These elements would normally condense into clouds in the lower atmosphere; however, they may be dragged to the upper atmosphere (and thus escape) by a sufficient mass flow rate of hydrogen.¹¹ With hydrodynamic models at hand, the CUTE data will provide a measure of the global mass loss rate, as well as the elemental abundances of elements, such as Mg and Fe. These NUV spectral lines probe the interaction between the planetary exosphere and the stellar wind, enabling CUTE to also investigate the interplanetary media of the host stars. Water is probably the most important infrared active species in hot Jupiter atmospheres, where it regulates the temperatures in the middle and upper atmospheres. OH is the primary dissociation product of water; detection of OH absorption in an exoplanet atmosphere would provide critical constraints on the fate of water in exoplanet atmospheres. OH can also act as a coolant, and detecting it with substantial abundances would provide new clues to the energy balance of the upper atmosphere.

Models of exoplanet magnetic fields predict radio emission¹⁵ and FUV auroral emission¹⁶ may be detectable from Jovian-mass planets in the solar neighborhood; however, these signals have not been conclusively detected,^{17–19} leaving the details of exoplanetary magnetism essentially unconstrained. Previous NUV transit observations of WASP-12b indicate an early ingress that has been interpreted in a number of theoretical scenarios, including a star-leading accretion stream supported by hydrodynamic mass loss,⁵ a plasma torus created by satellites of WASP-12b,²⁰ or a magnetically supported bow shock upstream of the planet's orbit.^{21,22} Subsequent HST transit measurements of WASP-12b, however, returned ambiguous results on the early ingress, suggesting potential stellar or planetary variability.^{2,4} CUTE will provide the sensitivity and temporal resolution necessary to discern between these scenarios if the early ingress is detected in a significant number of systems.

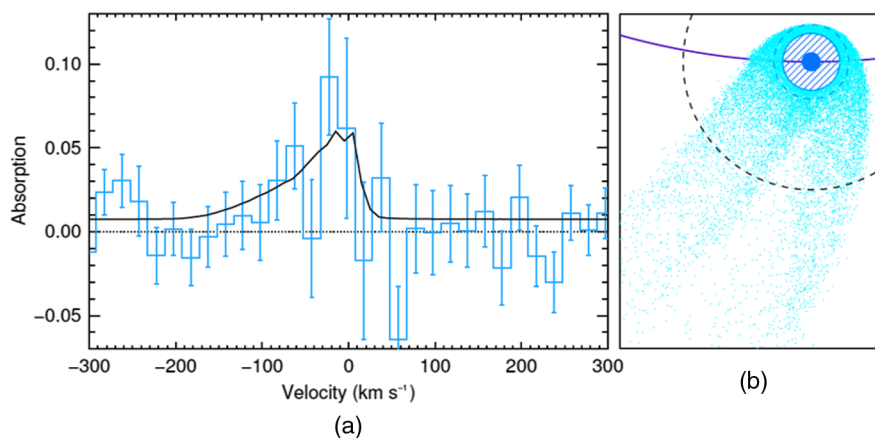


Fig. 2 (a) HST-STIS observations of neutral magnesium mass-loss from HD 209458b⁷ and (b) the hydrodynamic mass-loss model from Bourrier et al.¹⁴

Observing between 6 and 10 transits per system will enable CUTE to track variability and identify potential systematic errors. When combined with ground-based spectropolarimetric measurements of the stellar magnetic field, CUTE could potentially provide a detection and measurement of the planetary magnetic field itself.

The CUTE satellite will observe multiple transits of multiple hot Jupiter systems over the seven-month nominal mission timeline. Ground-based spectropolarimetric observations will be carried out in the northern and southern hemispheres mainly with ESPaDOnS, neo-NARVAL,²³ and HARPSpol, which members of the CUTE science team have institutional access to. We are currently targeting launching CUTE into a sun-synchronous orbit (SSO) to observe at least 12 systems with 10 observed transits each. The mission could be extended until deorbit depending on the health of the instrument at the end of the nominal mission.

3 Colorado Ultraviolet Transit Experiment Instrument Overview

A velocity resolution of $\lesssim 150 \text{ km s}^{-1}$ and an effective area sufficient to obtain 3σ transit detections to the geometric planet size transit depth ($\sim 1\%$) for all targets is desired. The designated spectral resolution enables CUTE to potentially resolve individual atmospheric absorption lines with widths on the order of those observed in HD209458¹⁴ on high signal-to-noise targets (e.g., KELT-9b). Owing to the overlap of many neutral and low-ionization atomic lines in the CUTE bandpass, the primary mass-loss and lightcurve morphology analysis can be carried out at reduced resolution in the event of unanticipated optical performance degradation. The CUTE system is designed to exceed these performance specifications by maximizing the telescope collecting area and utilizing high-quality optical elements, including UV-grade mirrors and a focusing, ultralow scatter holographically ruled grating. The aberration correcting grating and fold mirror result in a spectrum with low cross-dispersion flaring, minimizing the spectral extraction region on the detector (and thus the background equivalent flux) while optimizing the spectral resolving power to nearly the maximum possible (as limited by the detector pixel size) for the detector/bandpass combination selected. The rectangular aperture of CUTE is a new innovation for a CubeSat and represents more than three times the collecting area possible with a circular telescope. All other CUTE systems have flight heritage based on similar components flown on previous or upcoming missions. We present in the following sections an overview of the optical and mechanical design of the telescope and spectrograph (Sec. 3.1), a description of the detector focal plane array (Sec. 3.2), and a breakdown of the overall instrument performance (Sec. 4).

3.1 Optical Design

The CUTE aperture is rectangular in shape, featuring a $20 \times 8 \text{ cm}$, $F/0.75$ parabolic primary mirror feeding an $F/2.6$ classical Cassegrain telescope. We reference the F -number for this rectangular aperture to the longer axis of the telescope, which is the cross-dispersion dimension of the spectrograph. The large telescope aperture is made possible by the Blue Canyon Technologies (BCT) XB1 spacecraft bus, which provides critical systems, such as power, command and data handling, communications, and attitude control in a compact package that requires $<2\text{U}$ of the 6U spacecraft. The hyperbolic secondary mirror will be cantilevered off of

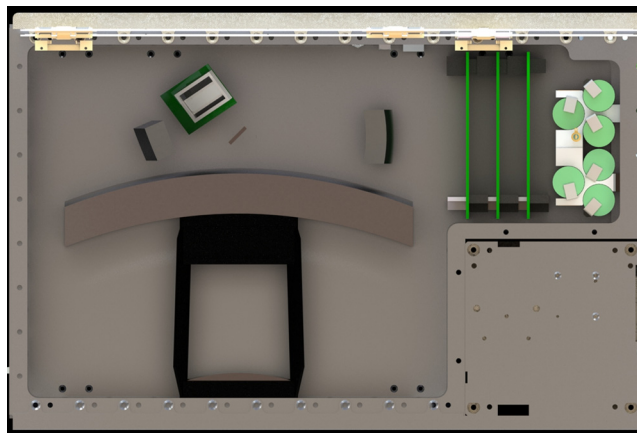


Fig. 3 CAD rendering of the CUTE optics, with a conceptual cartoon of the invar tower and telescope baffle, inside the BCT 6U spacecraft.

an invar central spire attached to the primary mirror baseplate via the primary aperture (Fig. 3). The telescope and mount structure will be fabricated, aligned, and vibration tested by Nu-Tek Precision Optics, with redundant vibration testing done by CU after delivery to verify alignment stability under launch loads.

The beam is folded 90 deg by a $5 \times 2.5\text{-mm}$ flat mirror positioned 10 mm before a $200 \mu\text{m} \times 3.5 \text{ mm}$ ($80'' \times 1400''$) slit at the Cassegrain focus. The slit assembly will be polished and angled 45 deg about the slit axis (reducing the projected slit width to $\sim 100 \mu\text{m}$) to reflect the remainder of the field onto a ground service aspect camera for alignment to the BCT spacecraft during integration. The beam is diffracted, magnified, and focused by a spherical $R = 86.1 \text{ mm}$, 1714 gr/mm aberration correcting ion-etched holographic grating of the type used in HST-COS²⁴ and ruled by Horiba J-Y. A second fold mirror with an $R = 300\text{-mm}$ cylindrical shape about the cross-dispersion axis adds an additional layer of aberration correction and positions the focal plane to maximize the volume available for the detector. There are some polarization effects induced by the grating and fold mirror that are not anticipated to influence the science but will still be measured during testing and are accounted for in throughput calculations (Sec. 4.1). The final beam focal ratio is $F/5.5$, yielding a detector platescale of $208'' \text{ mm}^{-1}$.

Nu-Tek will fabricate a mounting and metering assembly that will attach to the BCT spacecraft via the primary mirror baseplate and feature mounts for the spectrograph optics and slit assembly, whereas the grating and fold mirror will be installed and aligned at CU. Blackened baffles will be fabricated into the optical structure to suppress stray light between all optics (Sec. 6). There has been recent progress in the fabrication of vacuum-safe baffles using 3-D printing, enabling more complex designs that will increase the stray light rejection.²⁵ We will investigate the feasibility of using these materials and methods for the CUTE baffle system. A raytrace of the optical system is presented in Fig. 4, and the optical prescription is presented in Table 1.

3.2 Detector System

The spectrum is imaged onto an e2v CCD42-10 back-illuminated, UV-enhanced CCD detector. The CCD42-10 has an active area of $27.6 \times 6.9 \text{ mm}$ with 2048×515 pixels, each $13.5\text{-}\mu\text{m}$ square. The CCD42-10 has flight heritage as the sensor

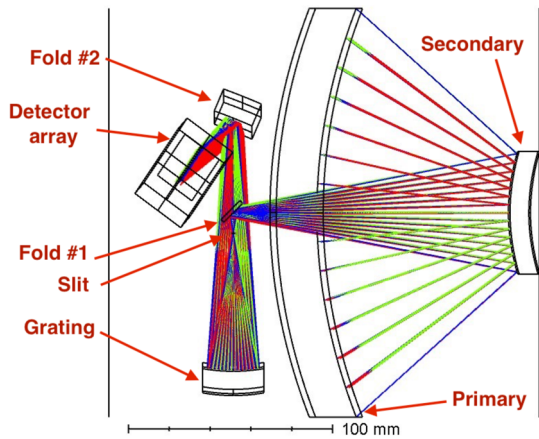


Fig. 4 Annotated raytrace of the CUTE spectrograph. The vertical black lines denote the front and back walls of the BCT spacecraft. The dispersion direction is out of the page. The detector footprint is the inner surface, with an outer surface showing the footprint with mount.

used on the Mars Science Laboratory ChemCham LIBS spectrometer.²⁶ The CCD will be cooled to Peltier temperatures between $-50^{\circ}\text{C} \geq T_{\text{CCD}} \geq -60^{\circ}\text{C}$ by a Marlow RC3-2.5 thermal electric cooler in thermal contact with a Cu heat sync and spacecraft radiator system, resulting in a dark background rate of $1.2 \times 10^{-2} \text{ e}^{-} \text{ pixel}^{-1} \text{ s}^{-1}$. The read noise is $3.5 \text{ e}^{-1} \text{ pixel}^{-1}$ RMS at the desired CUTE readout speed of ~ 20 seconds per frame, resulting in a total background per pixel per exposure of 15.85 counts (Fig. 5). The CCD is mounted near the sun-facing backside of the CUTE spacecraft and therefore will require thermal blanketing between the cooled system and the spacecraft bulkhead. The XB1 and associated CCD electronics, as well as the batteries, will be located at the far corner of the spacecraft to be as far from the cooled CCD as possible (Fig. 3).

The University of Colorado Laboratory for Atmospheric and Space Physics (CU/LASP) is in the process of installing a dedicated S-band receiver for CubeSat downlink communications. CUTE will be equipped with a BCT software defined radio S-band transmitter with an anticipated downlink capacity of ~ 1 Mbps, and a Spacequest TRX-U ultra high frequency (UHF) transceiver radio (19.2 Kbs) for nominal spacecraft operation and as a backup. This yields a projected daily data capacity of ~ 1.4 Gb assuming two ~ 12 min passes per day and no resource conflicts.

Full frame readouts of the CCD will only be transmitted to ground approximately once per day due to data bandwidth limitations. These full frames will be used for CCD health checks and to ensure that the spectral extraction routine is functioning properly. A typical science exposure will be processed on-board by first determining the location of the spectrum, and then extracting a subframe consisting of $\sim 20\%$ of the CCD height (~ 100 pixels, centered on the spectrum). More than 70% of the spectral energy of CUTE is contained within a spectral height of three pixels, with $>99.9\%$ contained within 7 to 11 pixels at the points of smallest and largest spectral flaring, respectively. Extraction over 100 pixels should, therefore, be more than sufficient for scientific analysis, and will reduce the maximum daily data rate to <0.7 Gb per day, including overheads—a rate that could be covered by a single data pass. An on-board processing system that extracts the spectrum and

Table 1 CUTE parameters.

CUTE instrument summary	
Focal ratio	$F/5.5$
Resolving power (R) at 3000 Å	3700
Waveband (total)	2515 to 3335 Å
Field of view	23.0'
Instrument platescale	$208'' \text{ mm}^{-1}$
Instrument effective area (3000 Å)	29.3 cm^2
Total focusing length	482.7 mm
Total instrument length	195.0 mm

Cassegrain parameters	
Primary dimensions	$200 \times 80 \text{ mm}$
Secondary dimensions	$68 \times 26 \text{ mm}$
Primary radius	300 mm
Secondary radius	-129.6 mm

Spectrograph parameters	
Blaze wavelength	2800.0 Å
Incident angle (α)	8.7 deg
Output angle (β)	20.6 deg
Line density	1714 gr mm^{-1}
Grating radius	86.1 mm
Grating dimensions	$31 \times 31 \text{ mm}$
Fold mirror dimensions	$25 \times 25 \text{ mm}$
Detector dimensions	$27.6 \times 6.9 \text{ mm}$

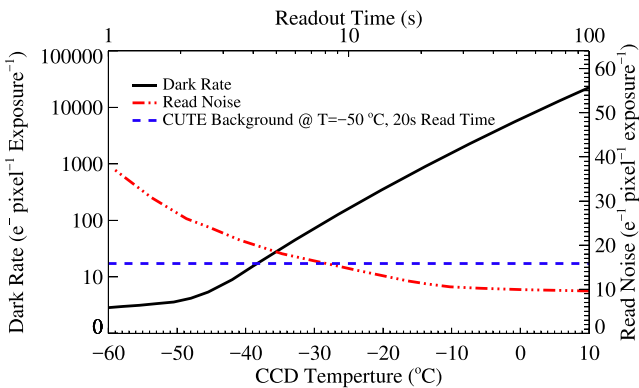


Fig. 5 A plot of the CUTE dark per pixel per 300 s exposure as a function of temperature (black), the counts per pixel as a function of readout time (red, note: not RMS read noise, but counts per pixel), and the total CUTE background per pixel per exposure for -50°C and 20 second readout (blue dash, referenced to the read noise axis).

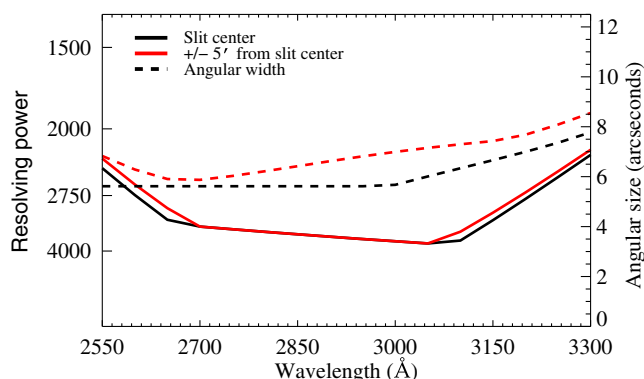


Fig. 6 Spectral resolving power and angular resolution of CUTE as a function of wavelength for the center and $\pm 5'$ of the FOV.

generates a 1-D data table will be developed in the event that the S-band transmitter fails and the slower UHF radio is used. Raw data of the transits will be stored on-board for up to one month and therefore can be reanalyzed as a full frame if needed.

4 Instrument Performance Estimates

The magnifying imaging spectrograph design follows that of the University of Colorado sounding rocket payload SISTINE.²⁷ With a final focal ratio of $F/5.5$ and a platescale of $208''\text{mm}^{-1}$, CUTE achieves an angular resolution of $5.6''$ and an average resolving power of >3000 across the operational bandpass. The spectral resolving power is limited by the size of the CCD resolution elements (defined as two $13.5\ \mu\text{m}$ pixels) from 2650 to 3100 Å, and the angular resolution is similarly detector limited from 2550 to 3000 Å, meaning that the RMS spot width at each wavelength in the dispersion and x -dispersion directions is smaller than the width of two pixels, or one resel (Fig. 6). More than 70% of the energy for any single wavelength is contained within a 2×2 pixel resolution element from 2600 to 3100 Å (Fig. 7). The pointing accuracy of the BCT XB1 spacecraft is listed at $7.2''$, with the RMS jitter during a 5 min exposure being somewhat smaller, but not yet well defined. This is well matched to the $5.6''$ scale of a resel and will contribute to a slight degradation of the final CUTE performance. CUTE utilizes a long slit despite point source targets so that the target can be moved around on the CCD chip in the event of radiation or other damage over the course of the mission.

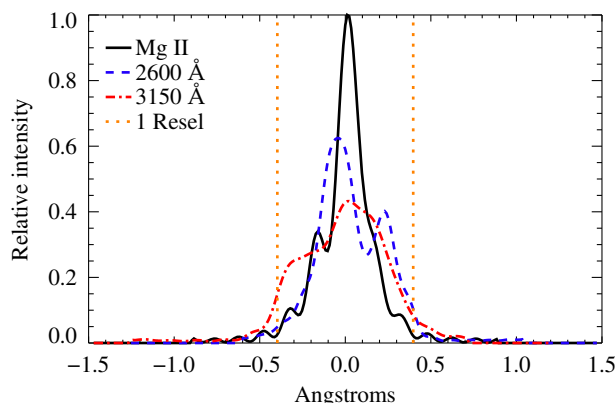


Fig. 7 Selected spectral line spread functions of CUTE, with the width of one resolution element overplotted (dotted lines).

4.1 Effective Area

The effective area of CUTE is the product of the clear collecting area of the rectangular telescope (A_T) and the individual component efficiencies

$$A_{\text{eff}}(\lambda) = A_T R(\lambda)^5 \epsilon_g(\lambda) D_{\text{QE}}(\lambda), \quad (1)$$

where $R(\lambda)$ is the reflectivity of the magnesium fluoride (MgF_2) protected aluminum-coated optics, $\epsilon_g(\lambda)$ is the grating efficiency, and $D_{\text{QE}}(\lambda)$ is the quantum efficiency of the e2v CCD42-10 detector as reported by e2v. $\epsilon_g(\lambda)$ is the modeled blazed grating efficiency curve for the CUTE grating as predicted by Horiba J-Y. The peak efficiency of 65% is comparable with the peak efficiency achieved for similar ion-etched blazed holographic gratings on HST-COS in the FUV (the NUV COS gratings had a unique ruling pattern that led to reduced efficiency).²⁸

CUTE will utilize $\text{MgF}_2 + \text{Al}$ as opposed to bare aluminum for the optical coatings to prevent the formation of an oxide layer (Al_2O_3) on the aluminum. Oxide formation can interfere with grating performance, which can result in efficiency degradation. The CUTE $\text{MgF}_2 + \text{Al}$ optical coatings on the grating and second fold mirror will be applied by the NASA Goddard Space Flight Center (GSFC) Thin Films Coating Laboratory, whereas Nu-Tek will deliver a coated telescope and first fold mirror. With properly optimized thicknesses, the GSFC process has been shown to produce coatings with reflectivities as high as 94%; however, we chose to model A_{eff} with a more conservative $R(\lambda) < 90\%$. The combined predicted CUTE performance curve with component efficiencies is presented in Fig. 8.

4.2 Sources of Systematic Uncertainty

Transit observations require a robust understanding of systematic error, as instrumental or stellar variability over a ~ 2 -h transit could significantly skew results. The CUTE team, led by CU/LASP and the Space Research Institute of the Austrian Academy of Sciences, has begun developing a data simulator to analyze the impact of potential noise sources (thermal fluctuations, scattered light, cosmic rays, etc). This simulator will help drive a robust instrument calibration and testing program at CU/LASP to characterize the CUTE instrument on the ground and in orbit prior to and during science operations.

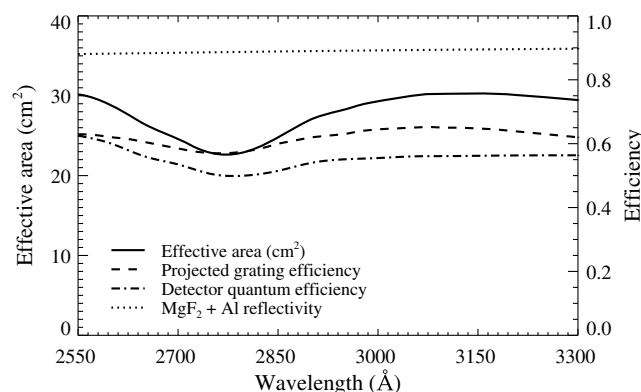


Fig. 8 The effective area curve for CUTE derived from Eq. (1) with component efficiencies overplotted.

Many potential systematic errors inherent to transit spectroscopy were taken into account when the CUTE mission was designed. Certain astrophysical sources, such as stellar variability, will be mitigated by the sheer observation time available. CUTE will observe approximately half of a full orbital phase of each planet target for each transit, providing hours of baseline for each host star. Random or unexpected short-term events, such as residual cosmic rays or interloping objects, will likewise be mitigated by the number of transits observed (≥ 10 per target), as the data for any outlier transit will be downloaded in full and studied in more detail. The SSO of CUTE will put the spacecraft into a state of near-thermal equilibrium, limiting thermal variability on both the optical bench and detector. Instrumental performance degradation on-orbit and spacecraft pointing errors (resulting in the spectrum being imaged on different portions of the detector) will be accounted for by a robust on-orbit calibration program. Up to one full day of observation time per week is currently available for calibration if needed, including observing standard stars at any detector location. A more detailed analysis will be possible once the CUTE instrument has been fabricated.

5 Science Operations

CUTE will have a nominal operational lifetime of 7 months, with the first month consisting of health checks and on-orbit calibrations. During the 6-month primary science mission, CUTE will observe exoplanet transits of hot Jupiters around a sample of ~ 12 bright stars (out of a sample of up to 30 candidate stars within reach of CUTE) with a broad range of spectral types (see Table 2 for a subset of possible targets). The list of candidate stars will increase as new discoveries are announced by ground and space surveys (e.g., KELT, TESS, and MASCARA). Each target will be prioritized based on the number of available transits during the operations window,

the signal-to-noise of the transit, and the scientific relevance of the target. It is anticipated that CUTE will observe 10 transits from each of 12 unique targets during the 6-month mission lifetime in an SSO, with a lesser number of transits from other targets interspersed when there are no higher priority targets available (Fig. 9).

While the nominal mission is only seven months, the CUTE satellite will have an orbital lifetime of at least 1 year and could be extended until orbital decay. The nominal mission will be extended automatically after deployment until at least the end of the funding period of performance (June 2021), as much as 1.5 years if CUTE were to launch January 2020, as planned. Therefore, while we baseline at least 100 transits in the nominal mission, this number could more than double depending on the launch date and longevity of the spacecraft.

CUTE will observe each transit across half the exoplanet orbital phase ($-0.25 < \phi < 0.25$) to ensure a well-established stellar flux baseline. It is not certain when the early ingress transit will begin, as there is no foreknowledge of the extent of the atmospheres for most targets; therefore, the wide phase range will ensure that the ingress/egress will be captured. With an average planetary orbital period of 3 days, CUTE will typically observe 3 to 5 transits per week. Each primary target will be visited for multiple transits to ensure complete transit coverage and to search for variability in the transit shape and depth. CUTE will have $>70\%$ observing efficiency for most targets in the anticipated SSO, which will enable the majority of the light curve for each targeted transit to be observed continuously. CUTE is also compatible with an ISS or other equatorial orbit; however, Earth occultation will reduce observation efficiency to $\lesssim 40\%$ and require multiple transit observations to construct a full light curve. We anticipate only five transits of 12 targets as a baseline mission should CUTE be launched into such an orbit, as well as fewer ground

Table 2 CUTE preliminary representative target list.

Target	m_V	R_P (R_J)	Period (Day)	a_{orb} (AU)	RA	DEC	$T_{\text{eff},*}$ (K)	\dot{M}_P (kg/s)	Drag (kg/s)	S/N (Mg II)	S/N (Mg I)	S/N (Cont.)
HD-209458	7.7	1.36	3.53	0.047	22:03:10.8	+18:53:03.7	6065	10^8	9×10^6	102.2	72.1	204.2
HD-189733	7.7	1.14	2.22	0.031	20:00:43.7	+22:42:41.3	5040	6×10^8	2×10^7	61.4	28.5	104.8
WASP-33	8.3	1.50	1.22	0.026	02:26:51.1	+37:33:01.8	7430	3×10^8	3×10^7	115.7	88.5	180.8
KELT-7	8.5	1.53	2.73	0.044	05:13:10.9	+33:19:05.8	6789	10^8	10^7	101.4	77.8	159.3
WASP-18	9.4	1.27	0.94	0.020	01:37:25.0	-45:40:40.5	6400	2×10^7	10^8	61.2	47.8	98.7
HAT-P-22	9.7	1.08	3.21	0.041	10:22:43.6	+50:07:42.0	5302	2×10^7	3×10^7	13.5	5.6	25.4
WASP-74	9.7	1.56	2.14	0.037	20:18:09.3	-01:04:32.6	5990	3×10^8	10^7	26.8	19.3	62.5
WASP-14	9.8	1.28	2.24	0.037	14:33:06.4	+21:53:40.9	6475	10^7	10^8	48.4	38.2	79.2
WASP-8	9.8	1.04	8.16	0.080	23:59:36.1	-35:01:52.8	5600	4×10^7	3×10^7	25.1	18.1	58.9
XO-3	9.9	1.22	3.19	0.048	04:21:52.7	+57:49:01.8	6429	4×10^6	2×10^8	43.4	34.4	71.5
WASP-69	9.9	1.06	3.87	0.045	21:00:06.2	-05:05:40.1	4700	10^9	3×10^6	12.0	5.0	22.7
KOI-13	9.9	1.41	1.76	0.034	19:07:53.1	+46:52:05.9	7650	10^8	10^7	42.2	33.5	69.7
55-Cnc	6.0	—	14.65	0.11	08:52:36.1	+28:19:53.0	5196	3×10^7	10^7	157.7	78.7	255.3

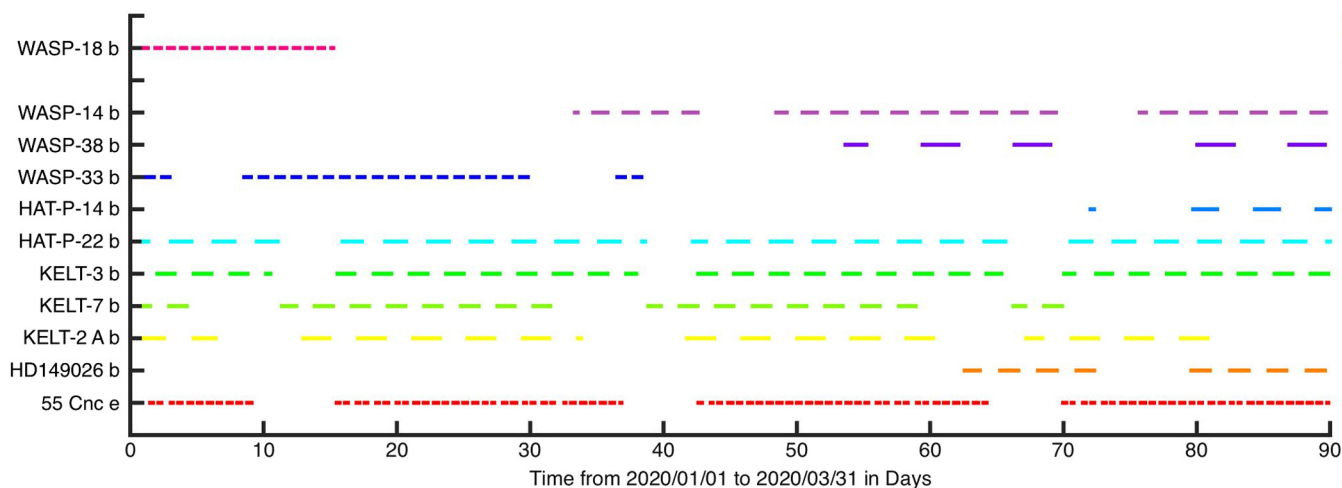


Fig. 9 Transit visibility windows for an SSO in a 3-month period starting January 1, 2020, for a selection of possible CUTE targets. The transit phase sampled is $-0.25 < \phi < 0.25$. Gaps are due to the planet being out of transit, or the Earth, sun, or moon violating an avoidance angle condition.

station contacts per day, as an equatorial orbit will not pass over the second LASP ground station in Fairbanks, Alaska. A proposal to the NASA CubeSat Launch Initiative has been submitted requesting that CUTE be placed on the CubeSat launch manifest with an SSO.

Students at the University of Colorado are currently developing an algorithm to optimize the operational efficiency of CUTE. This algorithm projects the availability of all targets on the sky for a given orbit, the transit phase, and the scientific relevance to select the most valuable target for observation at any given time (Fig. 9). Exclusion angles for the sun, moon, and Earth are all accounted for. The science team will then select from the ranked targets an observing plan on a week-by-week basis, updated as data are analyzed and the science priorities are reassessed. We find that CUTE will be capable of meeting the goal of at least 10 transits of 12 systems within the baseline mission lifetime.

5.1 Scientific Capabilities

Figure 10 shows a simulated 300 s CUTE spectrum of HD 209458, one of the brighter stars in the CUTE sample ($V_{\text{mag}} = 7.6$, $T_{\text{eff}} = 6000$ K, Table 2). These count rates are

consistent with an average SNR > 18 per resolution element based on the backgrounds projected in Fig. 5. The integrated absorption regions near MgII and MgI will likewise have an SNR > 50 , making CUTE sensitive to transit depths as low as 0.1% to 1% when folded over two or more transits. With sufficient signal-to-noise folded over multiple transits, it may be possible to resolve other individual atmospheric absorptions lines/bands. The transit depth is expected to be 4% to 10% in atmospheric tracers, such as around MgI and MgII.^{1,2,14}

We simulated CUTE observations of 10 transits of HD 209458b with an ISS orbit (40% covering fraction per orbit), assuming the MgI transit model of Bourrier et al. CUTE samples the entire light curve from $-0.25 < \phi < 0.25$ over the 10 transits with the precision to sample the ingress and egress of an extended atmosphere (Fig. 10). The projected SNR for a band of spectrum within ± 10 Å of the center of the neutral and singly ionized Mg lines, as well as for a 50 Å band of the continuum, for a subset of possible CUTE targets is presented in Table 2. We integrate over a large bandpass rather than fit the MgII line profiles to encompass multiple singly ionized gas species around the MgII feature.^{1,4} Similarly, we integrate over a large “line-free” continuum region near 2900 Å as a comparison point with optical transits. For specific

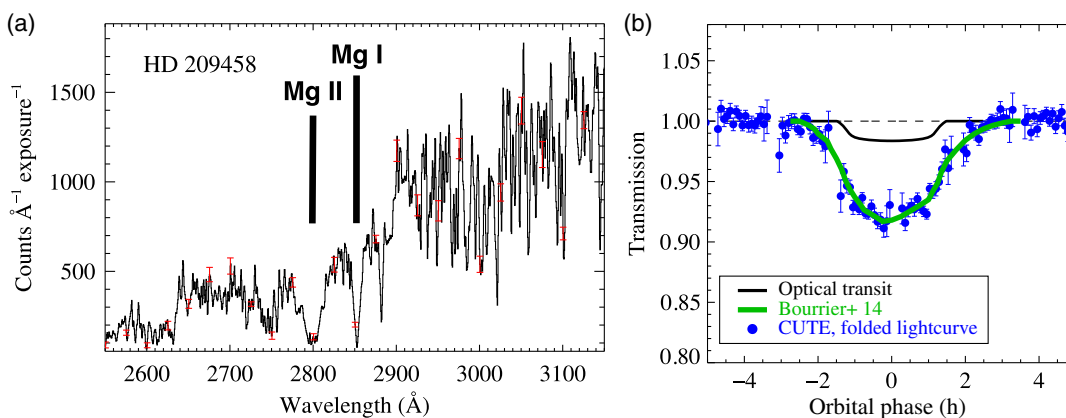


Fig. 10 (a) Simulated 300-s CUTE spectrum of HD 209458. (b) The folded lightcurve of 10 simulated MgI transits of HD 209458b as observed by CUTE, based on the model of Bourrier et al.¹⁴ The background and simulated spectrum from the left is folded into this simulation.

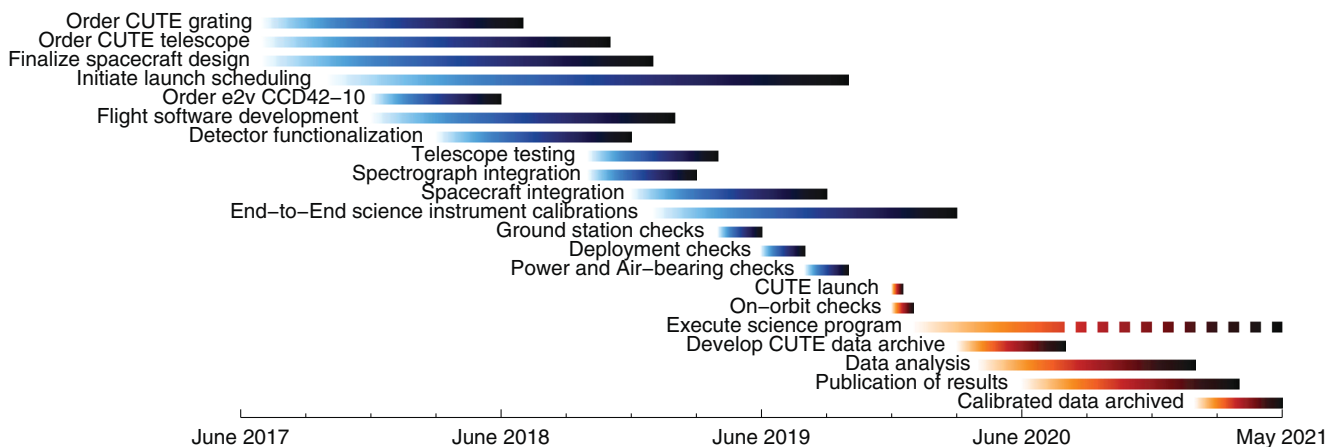


Fig. 11 Anticipated CUTE fabrication and launch schedule.

bright, early type targets (e.g., KELT-9b), high-SNR (>50 per spectral resolution element) spectra can be acquired in a single transit observation.

5.2 Science Closure

CUTE is anticipated to provide ~ 10 transit light curves ($>60\%$ coverage over a $-0.25 \leq \phi \leq 0.25$ phase range) of ~ 12 short-period exoplanets by the end of the nominal 7-month mission. A number of other planetary systems will be observed per the discretion of the science team during scheduling gaps (see Fig. 9). This data will represent more than an order of magnitude increase in the number of spectroscopic NUV transits observed to-date, bringing the observational basis for atmospheric escape studies on par with hydrodynamic models of exoplanet atmospheric mass loss (Sec. 2).^{9–12} CUTE will help to resolve the ingress variability observed in systems like WASP-12b by covering a large number of transits per system,^{2,4} and likewise address the effect of stellar variability in the data by significant out-of-transit monitoring. Measurements of this breadth are not feasible with a shared resource, such as HST, the only existing observatory capable of these observations. Complimentary ground-based spectropolarimetric observations of the stellar magnetic field could potentially provide information on the planetary magnetic field as well.³ The expected on-orbit lifetime of CUTE is 2 years, enabling a possible extended mission, increasing the final CUTE database to 24 to 30 close-in planets. With all data products publicly available, we expect CUTE to make a significant contribution to the study of atmospheric mass loss in exoplanet systems.

6 Colorado Ultraviolet Transit Experiment Development and Testing Schedule

Funding for the fabrication of CUTE began in July 2017, and orders are being assembled for long lead time items, including the grating and telescope optics (Fig. 11). The grating has an estimated delivery date from Horiba J-Y of March 2018, while we anticipate that the assembled, aligned, and focused telescope will be delivered by Nu-Tek in late 2018. Following delivery of the telescope, we will perform a quality review that will include throughput testing, spot size measurement, and another vibration test. The CCD42-10, as well as two engineering chips, will be delivered in early 2018 and the process of creating a functional controller and mount for

the CCD chip and designing and testing the thermal mount will proceed throughout 2018. The grating will be delivered coated in platinum for preliminary efficiency and dispersion measurements in the CU square tank facility, after which it will be sent to GSFC for a $\text{MgF}_2 + \text{Al}$ coating. After a postcoating reflectivity measurement, the spectrograph will be installed on the telescope (see Sec. 3.1). Spectrograph focusing and alignment will be achieved via a piston-tip/tilt grating mount. The assembled science instrument will be illuminated with collimated light from a D_2 or PtNe lamp installed onto the CU long tank facility for final system alignment using the science detector.

There will be a direct path to the first fold mirror for a region of sky subtending a total of 1310 deg^2 due to the large aperture and fast primary mirror ($F/0.75$). Although not all of this will reflect into the slit, we assume all of it does for the sake of estimating the “worst-case” scattered light background. We assume a conservatively high flux density of $10^{-7} \text{ erg cm}^{-2} \text{ \AA}^{-1} \text{ s}^{-1} \text{ deg}^{-2}$ in the NUV, or roughly the equivalent of one Sirius deg^{-2} . The CUTE spectrograph will be fabricated with light trapping baffles machined into the mount structure that will require a minimum of three bounces for a photon incident on the baffle to escape on a vector toward the next optical element, and at least two such reflections for off-axis light to align sufficiently with the optical path to reach the detector, which faces away from the slit (Fig. 4). The light traps will be fabricated from a blackened material, such as roughened black delrin, invar, or black anodized and roughened aluminum with $<3\%$ reflectivity in the near UV, suppressing the scattered light by a minimum of nine orders of magnitude ($0.03^6 < 10^{-9}$). This will limit the photon flux to $<50\%$ of the dimmest CUTE target, which when isotropically distributed around the detector will represent a background of $<1\%$ per resel for this worst-case scenario. Rigorous scattered light testing will be carried out at CU using an Hg “pen-ray” to illuminate the telescope aperture with intense off-axis NUV radiation.

End-to-end testing will proceed starting in mid 2019 after integration into the XB1 spacecraft. CUTE will be subjected to thermal vacuum testing in CU/LASP facilities to demonstrate system survivability and optical stability. Handshaking and communications testing will proceed in late 2019 via the LASP ground station, which has successfully served as the Mission Operations Center for other LASP-built CubeSats

utilizing the XB1 system, including MinXSS.²⁹ The target launch date for CUTE will be in early 2020 to any orbit visible from the CU ground station, including an ISS or an SSO. Nominal science operations will be carried out for at least 7 months from deployment, with one month of on-orbit commissioning and 6 months of science operations. A data reduction pipeline is being designed by the Space Research Institute of the Austrian Academy of Sciences to handle the on-board data processing, including the background subtraction, cosmic-ray rejection, and flat fielding of each CCD frame and the generation of a 1-D spectrum for transmission to the ground. A portion of the raw data will also be transmitted and analyzed on the ground (Sec. 3.2). Calibrated, background subtracted 1-D spectral data will be made publicly available on CU-LASP servers at the conclusion of the mission.

7 Summary

The University of Colorado UV instrumentation group at the Laboratory for Atmospheric and Space Physics has finalized the design of the CUTE and will begin fabrication in 2018. CUTE is a low-resolution ($R \approx 3000$) NUV imaging spectrograph with spectral coverage of important exoplanet atmospheric tracers of Mg, Fe, and OH. A rectangular aperture results in greater than three times the collecting area relative to a circular aperture in a 6U CubeSat form factor. The average effective area of CUTE is 28 cm², or $\approx 70\%$ of the effective area (and $\approx 40\times$ the resolving power) of the GALEX NUV grism, delivered in a 6U CubeSat package. The high-quality spectral and angular resolution, which produce monochromatic point source images smaller than a single resolution element on the detector, is made possible by a multipassed optical design and a blazed, ion-etched aberration correcting holographic grating. CUTE will be the first NASA-funded UV/O/IR CubeSat for scientific astronomy, and is designed to demonstrate that high-quality science data can be obtained from an instrument in a CubeSat package and a suborbital class budget. The target launch date for CUTE is early 2020, after which CUTE will embark on a nominal 7 month mission to monitor the transits of hot Jupiter exoplanets to quantify atmospheric mass loss and magnetic fields.

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Brian T. Fleming is an assistant research professor at the University of Colorado, Boulder, and NASA Nancy Grace Roman Technology Fellow specializing in space instrumentation and energetic radiation escape from galaxies. He is the optical designer and project scientist for a number of NASA suborbital programs and serves on the instrument definition team for the LUVOIR UV spectrograph LUMOS.

Kevin France research focuses on exoplanets and their host stars, protoplanetary disks, and the development of instrumentation for

ultraviolet astrophysics. He was a member of the HST-COS instrument and science teams, a voting member of the LUVOIR STDT, is a regular guest observer with the Hubble Space Telescope, and is the PI of NASA-supported sounding rocket and small satellite programs to study exoplanet atmospheres and flight-test critical path hardware for future UV/optical missions.

Nicholas Nell is an aerospace engineering graduate student at the University of Colorado working on the SISTINE sounding rocket project. He formerly served as the electrical engineer for the CU UV astronomy instrumentation group.

Richard Kohnert: Biography is not available.

Kelsey Pool is an undergraduate student at the University of Colorado Boulder studying Mechanical Engineering. Currently, she is a research assistant on the CUTE CubeSat project.

Arika Egan is an astrophysics and planetary science graduate student at the University of Colorado, Boulder, working on the CUTE CubeSat project.

Luca Fossati is a junior group leader at the Space Research Institute of the Austrian Academy of Sciences studying exoplanet atmospheric escape.

Tommi Koskinen is an assistant professor at the Lunar and Planetary Laboratory of the University of Arizona. He is an expert on the physics and chemistry of the middle and upper atmosphere. His research combines the analysis of remote sensing data with numerical modeling to characterize planetary atmospheres in a wide range of different environments, ranging from the solar system to distant exoplanetary systems.

Aline A. Vidotto is an assistant professor of physics at Trinity College Dublin specializing in the interaction of exoplanets with their host star's wind.

Keri Hoadley is a postdoctoral researcher at the California Institute of Technology studying space instrumentation. She received her PhD from the University of Colorado in 2017.

Jean-Michel Desert is an assistant professor of astronomy and astrophysics at the University of Amsterdam (UvA) in the Netherlands studying exoplanets and their atmospheres.

Matthew Beasley is an astronomer specializing in UV instrumentation and cubesats.

Pascal M. Petit is an astronomer at IRAP (Toulouse University) specializing in stellar magnetic fields and exoplanets.